GEOLOGICAL SERIES

OF

FIELD MUSEUM OF NATURAL HISTORY

Volume VII | August 30, 1949 | No. 8

THE NAVAJO METEORITE

By

Sharat Kumar Roy
Chief Curator, Department of Geology

and

Robert Kriss Wyant
Curator, Economic Geology

INTRODUCTION

Preliminary studies on the Navajo meteorite described in this paper were made by the late Dr. Oliver Cummings Farrington and Mr. Henry W. Nichols, both former Chief Curators of the Department of Geology, but, for various reasons, the studies were never completed. Fortunately, notes on their results were kept in the files, and these we have been able to use to advantage. We wish to acknowledge our indebtedness to our predecessors in the study of this meteorite.

NAVAJO

Near Navajo, in Apache County, Arizona, United States of America.
Latitude 35° 20′ N., Longitude 109° 30′ W.
Iron, nickel-poor ataxite (D_2).
Found 1921 and 1926 (two masses).
Total weight 2,180 kilograms (4,814 pounds).
Catalogue numbers, Navajo I, Me 2038; Navajo II, Me 2099.

This is an iron meteorite of more than ordinary significance. An account of its features of special interest will be found on page 118, under the heading "Structure and Constituents."

The meteorite consists of two masses, both of which are remarkable for their size. The larger mass, designated as Navajo I (figs. 45, 46), weighs 1,499.6 kilograms (3,306 pounds); the smaller, designated as Navajo II (fig. 47), weighs 680.4 kilograms (1,508 pounds), making the total known weight of the fall 2,180 kilograms (4,814 pounds).

Navajo I was found July 10, 1921, about thirteen miles from Navajo, in Apache County, Arizona. It was buried in talus at the foot of a ridge of Shinarump sandstone. The finders were Messrs. Robert K. Thomas and Carl Hill, both residents of Navajo. At the time negotiations for the acquisition of the meteorite were in progress, Mr. Thomas stated in a letter to the Museum (dated

FIG. 45. Navajo I, showing a deep fissure that extends half way around it. The chisel marks referred to (see below) are also shown. About $\times 1/6$.

January 1, 1922), "The Navajo meteorite . . . was known to the Navajo Indians since they came to this country about 1600(?) . . . and was covered up with rocks to keep the white man or other tribes from finding it as they thought it sacred. They called it 'Pish le gin e gin' (black iron). They tell me that the marks were there when they first found it and they think the prehistoric pottery-makers cut them in."

The marks referred to in the letter do not appear to be anything more unusual than marks made by someone in an effort to determine the nature of the mass. It should, however, be pointed out here

that the chisels used to make the marks had wider blades than those generally used now, and that picture writings were found on rocks in nearby outcrops.

Navajo II was discovered five years later. It lay about 160 feet northwest of Navajo I, buried in soil formed by outwash from the neighboring ridge. An upright rock was found standing beside it.

FIG. 46. Navajo I. View of side opposite that shown in figure 45, showing another smaller fissure. About $\times 1/6$.

This supports the view expressed by Mr. Thomas that the meteorite had been known to the Navajos for decades prior to its find. Both masses, with the exception of a few small slices cut for study, are now on exhibition in this Museum.

SHAPE, SIZE, AND SURFACE CHARACTERISTICS

NAVAJO I.—Navajo I is roughly spheroidal in form, with an average diameter of 28 inches (figs. 45, 46). Its surface has suffered considerable oxidation and is of rust brown color, but, owing to the arid climate of the region, the oxidation has not penetrated deeply.

Pits of irregular form, which characterize the exterior, were formed at the time of the fall, and no marked differentiation of the pits, which might indicate orientation of the mass, can be observed. In general, the pits are from one to three inches broad and not more than a quarter of an inch deep. Some, however, are only about one-fourth of an inch in diameter and correspondingly shallow. Still less numerous, but more unusual in form, are pits as deep as, if not deeper than, their diameters. One such depression is one-half of an inch in diameter and three-fourths of an inch deep; others are not so deep, but are of about the same diameter. They suggest that a fusible constituent has melted out at these points. The surface of the meteorite, when found, was extensively coated with carbonate of lime, derived from the soil in which the mass was buried. Since its arrival at the Museum, much of this coating has been removed by dissolving it in acid, and, where it has been removed, the surface is black and smooth.

A peculiar feature of Navajo I is a deep fissure that extends half way around it, in some places reaching a depth of six inches. About three inches from this fissure and generally parallel to it, another extends for a distance of a little more than a foot. The edges and walls of the fissure are smooth and rounded, indicating that they were subjected to heat and erosion during the meteor's flight to the earth. They also indicate that the fissures were formed, not from the impact of the meteorite upon the earth, but from shock and air pressure after it reached the earth's atmosphere and prior to its fall. The finders of the meteorite stated that at the time of the find there were many loose fragments of the meteorite in the fissures. These fragments, with the exception of one, were dug out and carried away by souvenir hunters while negotiations for the purchase of the meteorite were in progress. The one fragment that was left had an irregular, finger-like shape and measured about two inches in length. Fragments such as these suggest that, unlike the fissures, the fractures were formed from the impact of the meteorite upon the rocky surface, and that considerable disintegration had taken place within them since the fall. Both the fissures and the fractures could have served as receptacles for the retention of water, which is an effective disintegrating and dissolving agent. Polished and etched slices of the meteorite reveal a number of veins of schreibersite of irregular width and varying course. In places these have decomposed to limonite, and, where the decomposition has advanced far enough, the slices are broken up into small pieces easily. It is not improbable that veins of schreibersite may have existed along the fissures, and

such a process of decomposition may have been in action, resulting in the formation of the fragments referred to above.

NAVAJO II.—Navajo II (fig. 47) is more elongated in form than Navajo I, its dimensions being 34 by 22 by 16 inches. Its surface is not fissured as is that of Navajo I, but the pittings on the two, even those that are of greater depth than width, are similar. Oxidation

FIG. 47. Navajo II. More elongated in form than Navajo I. It is evident that the two masses are individuals belonging to the same fall. About $\times 1/6$.

of the surface seems to have gone somewhat deeper than in Navajo I, and it had no coating of carbonate of lime.

CHEMICAL ANALYSIS

Samples for chemical analysis for both Navajo I and II were secured from an average of the borings obtained by a one-quarter-inch drill penetrating to a depth of two inches. During the drilling it was noticed that the first quarter-inch of the operation encountered much more resistance than the remainder. Moreover, the borings from this outer section were in the form of a powder, while beyond this point they were in the form of shavings. This would indicate that there had been a hardening or tempering of the surface of the meteorite due to the heat of the fall.

A total of five chemical analyses of the meteorite has been made, the earliest by Merrill (1922). Merrill, however, gave only the nickel content (5.81). The other four analyses were made in the Museum by H. W. Nichols and R. K. Wyant, using portions of the same samples. It will be seen from the following results of their analyses that the iron and nickel content are comparable, while there is some variation in the percentage of minor constituents.

H. W. NICHOLS, *Analyst*

Element	Analysis of Navajo I *Percentage*	Analysis of Navajo II *Percentage*
Fe	93.60	93.24
Ni	5.43	5.56
Co	0.14	0.13
Cu	0.02	0.005
P	0.41	0.372
S	0.10	0.056
Si	0.14	0.042
Ins	0.14	.....
Total	99.98	99.405

R. K. WYANT, *Analyst*

Element	*Percentage*	*Percentage*
Fe	93.62	93.34
Ni	5.37	5.60
Co	0.41	0.47
Cu	0.02	0.01
P	0.28	0.30
S	0.15	0.08
Si	0.10	0.07
Cr	0.02	0.03
Total	99.97	99.90
Specific gravity	7.82	7.80

As seen by the above results the two masses have essentially the same composition, and this fact, taken in connection with the similarity of their etching figures, surface characters, and close association as to locality, makes it evident that they are individuals belonging to the same fall.

STRUCTURE AND CONSTITUENTS

Megascopic examination of etched surfaces of Navajo I was made by Farrington, the results of which, as found in his notes, are as follows: "These, to the naked eye, present only a dull gray, homogeneous appearance, at once classing the meteorite in the group of ataxites. Under a lens, a section, when examined in reflected

light, shows abundant shining needles of rhabdite, quite uniformly distributed. These are rarely more than 0.5 of a millimeter in length and grade from this down to microscopic dimensions. Nearly all lie in one direction, parallel to one another. Scattered here and there are rectangular inclusions of schreibersite which are distinguished

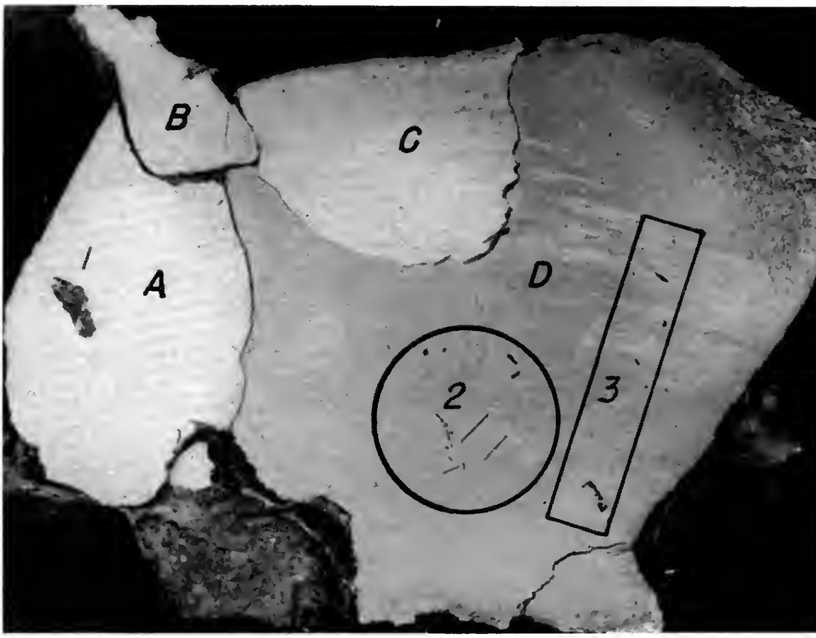

FIG. 48. An etched slice of Navajo II. Nital, 30 seconds. A, B, and C, brighter areas bounded by schreibersite veins. D, darker areas. 1, troilite inclusion bordered and traversed by schreibersite. 2 and 3, rhabdites with schreibersite inclusion. ×2.5.

by their form and larger size, some being 4 sq. mm. in area. These are for the most part near the periphery of the section. With a lens, too, some variations in color of the ground mass from light to dull-gray can be seen. Among the nickel-poor ataxites, to which, as can be seen later by reference to the analysis, this group belongs, the etched surfaces of the meteorite most resemble those of the Locust Grove."

Whether Farrington intended microscopic examination of the meteorite cannot be ascertained, but had he done so he doubtless would have observed additional features and perhaps would have modified some of the results he obtained. For reasons given later,

we have not studied the internal structures of Navajo I, but, based upon our studies of Navajo II, which is but a portion of Navajo I, we hardly can regard the Navajo meteorite as being of the same type as the Locust Grove. The chemical composition of the two does not differ appreciably, but structurally, according to Cohen (1897; 1905), the Locust Grove is granular, whereas the Navajo, as far as our studies show, is homogeneous. The size, form, and dispersion of the rhabdites and phosphide particles in the Locust Grove, as illustrated by Perry (1944), also differ conspicuously from those observed in the present meteorite. In addition, certain important structural features that characterize the Navajo meteorite are absent in the Locust Grove. These features are discussed later and illustrated by figures 50 and 51. The Museum has lent a slice of the Navajo I to Mr. Stuart H. Perry for metallographic studies. This is the same slice studied by Farrington and to which reference has already been made. Mr. Perry expects to publish the results of his work at an early date.

Of Navajo II, a broken-up, polished section consisting of several small pieces was available for study. Originally, the section measured 5 by 9 centimeters and weighed 150 grams. It is apparent that veins of schreibersite of irregular width and varying course traversed the section, and that the breaking up of the section into small pieces was the result of decomposition of these veins to limonite. One of the pieces, sufficiently large for study, was repolished and etched, using nital (5 per cent nitric acid) for periods ranging from a few seconds to five minutes (fig. 48).

It is well to point out here that for microscopic work the time of etching is highly important. Certain features that are visible in light etching may disappear or may not be visible in strong etching, and vice versa. No general rule, however, can be formulated regarding the time of etching required to observe a specific structure in a given meteorite. This is mainly because meteorites, even those that belong to the same group, may vary sufficiently in composition, structure, and relative hardness of their constituents to require different times of etching. An effective procedure to follow is to give a light etch to the specimen at first (for a second or less), gradually increasing the time and examining the specimen periodically between etchings. It will be found that light etching is almost imperative for work at high magnification, and that it is necessary to lower the magnification as the etching is made stronger.

The structure of the Navajo meteorite is that of a nickel-poor ataxite, consisting of a homogeneous mass of kamacite with an

abundance of schreibersite or nickel-iron phosphide, in the form of rhabdites and inclusions. Here the term rhabdite is used for only those forms of schreibersite that have needle-like structure; all others have been called inclusions, and, where necessary, their shape and size have been described. In addition, as referred to above, the section contains narrow, branching veins of schreibersite (fig. 48). The general appearance of the veins is that of a miniature stroke of lightning. The branches are not veins but cracks, barely visible to the

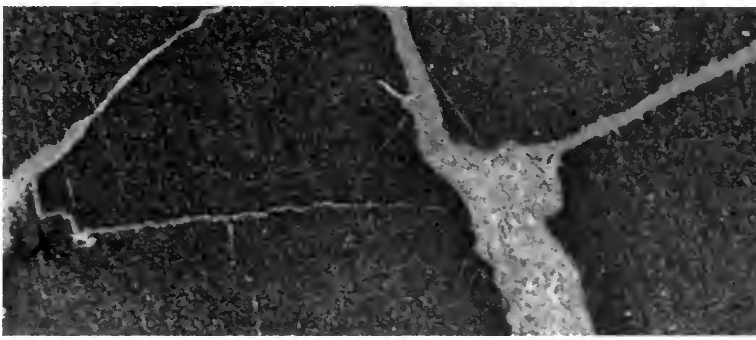

FIG. 49. Cracks at X leading from a schreibersite vein. The pattern is that of a cubic cleavage, characteristic of hexahedrites. ×15.

naked eye. They have a step-like pattern, resembling cleavage of galena (fig. 49). It may be that they are strain cracks that were formed later and that followed the original hexahedrite structure.

There are no traces of grain boundaries in the kamacite, except in one zone around a relatively large inclusion of troilite (fig. 54), but the surface of the kamacite that appears homogeneous under low magnification (×40) presents a feathery and mottled pattern when seen under high magnification (×320). The isolated nature of the grain boundaries indicates that they are remnants of previously established grains. The bulk of the schreibersite bodies is in the form of rhabdites and particles. The particles vary in shape from angular to irregularly rounded dots, and show little or no definite arrangement (figs. 50, 51). The form of the particles indicates diffusion, believed to be caused by reheating. The rhabdites or needles also vary in shape; some have wedge-like structure, but most of them are spindle-shaped (figs. 50, 52). They are arranged at right angles to one another, and appear, as it were, disposed along cubic planes. In the section examined, the needles occur mixed with the particles in three different areas, each of which is bounded by a schreibersite vein (fig. 48, A, B, C). These areas are silver-gray in

color and are visibly brighter than the remaining areas of the section, which are dull-gray (fig. 48, D) and, save for a few scattered diamond-shaped and rhombic schreibersite inclusions, occupied only by the irregularly rounded particles. The variation in color is due to the differences in the degree of surface reflection, the spindle-shaped

FIG. 50. Enlarged view of a portion of the areas C and D in figure 48. Left of the vein, irregularly rounded schreibersite particles with no definite arrangement. This area contains two sets of Neumann lines, but because of light etching they are barely visible. Right, spindle and wedge-shaped rhabdites oriented nearly at right angles to one another. One set of Neumann lines in this area. Neutral sodium picrate, 5 minutes. ×20.

rhabdites, because of their form and manner of dispersion, reflecting a greater amount of light. No satisfactory explanation, however, can be given here to account for the total absence of the spindle-shaped needles from the dull-gray area, which is separated from the other areas only by veins that are so narrow in places as to be hardly a millimeter wide. That the veins were a factor in causing the difference is suspected, but the processes leading to it are neither clear, nor understood. There are many examples in described meteorites of the occurrence of different-sized rhabdites, as well as gradations of rhabdites to flakes and particles of schreibersite, but so abrupt and conspicuous a change in form and orientation in such close proximity as is the case here, has not been reported. Nor are examples known of similar behavior of any mineral in terrestrial metamorphic rocks. There are good evidences of extra-terrestrial reheating of the meteorite and consequent metamorphism of some

of its constituents. The filling of the cracks with schreibersite to form veins, the presence of remnant grain boundaries, the alteration of kamacite bordering some of these veins, and the partial diffusion of the phosphide particles are all good indices of cosmic reheating.

Besides the two types of phosphide bodies discussed here, there are others, in the shape of slender, long needles, small squares,

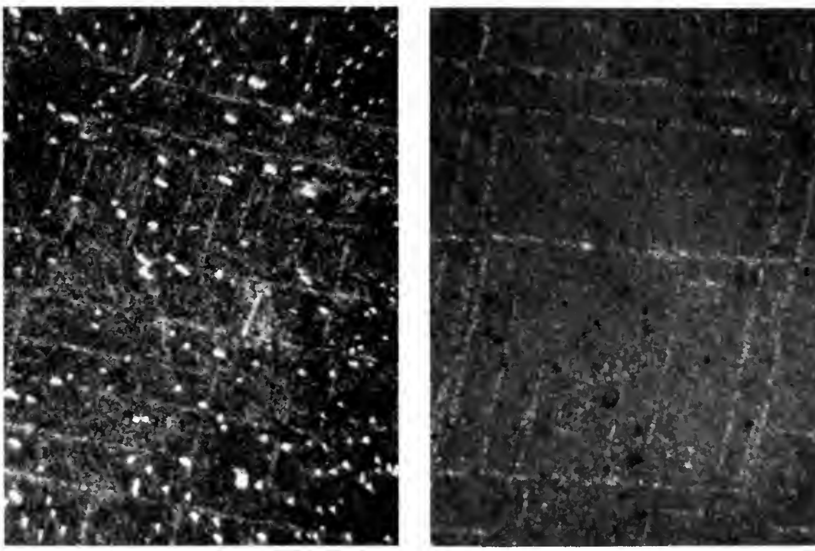

FIG. 51. Irregularly rounded schreibersite particles and lath-shaped bodies (area from figure 48, D) and two sets of Neumann lines. Left, diffusion of schreibersite particles at extreme upper left is apparent. Nital, 30 seconds. ×60. Right, area adjoining that shown to left but treated for 5 minutes with neutral sodium picrate. ×80.

rectangles and laths. These are scattered sparingly here and there without any definite arrangement except in one place, where a number of needles and squares are grouped together more or less radially (figs. 48–2; 54). It is useful to note here that the majority of these bodies are notched at one edge, giving the appearance of being corroded. Whether this is a primary or a secondary feature has not been determined. Of the other constituents, two troilite inclusions have been observed, one a mere dot, the other about 3.5 mm. long and 1.5 mm. wide (figs. 48–1; 54). The larger inclusion is bordered and in one place traversed by schreibersite. A third mineral in this inclusion, probably daubreelite, has been suspected but not confirmed. It is lighter in color than the other two but the grains are so minute and so intimately mixed that its isolation was

impractical. The color of the mineral, the presence of chromium in one of the analyses, and the fact that the meteorite is an ataxite, lend support to the possibility of its being daubreelite.

A most interesting feature of the meteorite is the presence of Neumann lines (figs. 50, 51). With the exception of Forsyth County,

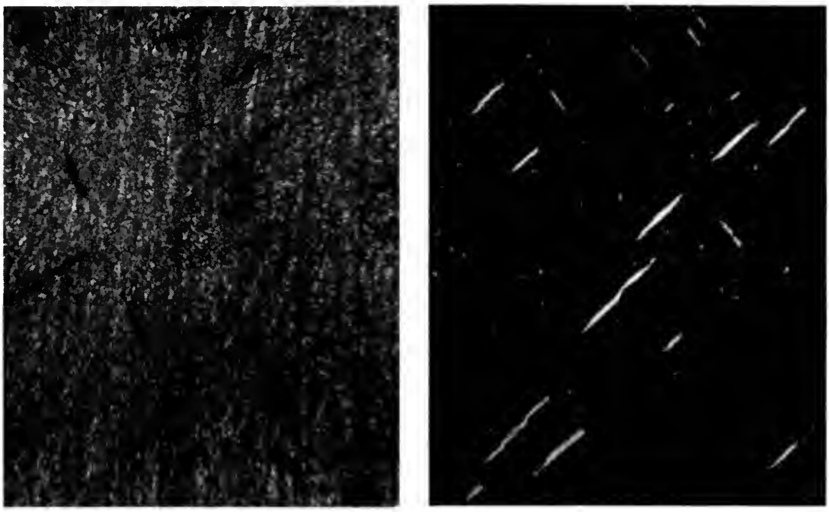

FIG. 52. Spindle- and wedge-shaped rhabdites (different areas from fig. 48, C). Both areas contain one set of Neumann lines (see fig. 50) that are not visible here. Left, treated with neutral sodium picrate, 5 minutes. Right, nital, 30 seconds. Print over-exposed to bring out schreibersite particles. ×180.

no other nickel-poor ataxite showing Neumann lines has, hitherto, been reported. Here again, as in the case of the two phosphide bodies, an abrupt change in the structure of the Neumann lines is manifest. In the areas (fig. 48, A, B, C) bounded by the schreibersite veins the Neumann lines consist of a single set. The lines are parallel and straight, but not always continuous, nor of uniform width, nor evenly spaced. In the remaining portion of the section (fig. 48, D), occupied only by the shapeless or irregularly rounded phosphide bodies, at least in the greater part of it, the Neumann lines consist of two sets of parallel lines—running diagonals of a cubic face. The lines in this area are also not of uniform width, nor are they evenly spaced.

It has been stated before that the meteorite has suffered cosmic reheating. On the basis of past laboratory experiments on the reaction of Neumann lines to heat, it can be assumed with reasonable

certainty that all pre-existing Neumann lines, if there had been any, were obliterated during reheating. The present Neumann lines, therefore, in all probability, were formed subsequent to reheating. The question now arises if they were formed before or after the meteor entered the earth's atmosphere. There is, of course, no proof that

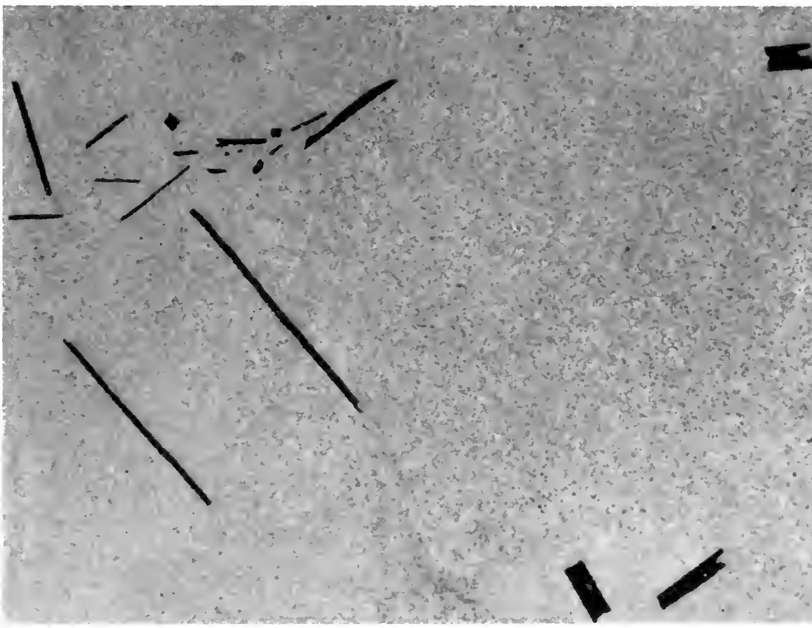

FIG. 53. Rhabdites and schreibersite inclusions of varying shape and size (area from fig. 48, D). Ends of many of these bodies are notched. Neutral sodium picrate, 5 minutes. ×19.

they were not formed cosmically subsequent to reheating. But there is good circumstantial evidence suggesting that they were formed during the meteor's flight to the earth. The meteorite was found in two masses, indicating that the original body was disrupted. Furthermore, one of the masses was deeply fissured. Both of these occurrences—the disruption and the production of deep fissures—are conclusive proof that the meteor during its flight encountered severe air pressure and resulting disruptive stresses. Since Neumann lines have been produced in the laboratory by subjecting artificial irons to violent shock and extensional stresses (Foley and Howell, 1923; Foley and Crawshaw, 1926), there would seem to be reason for supposing that the Neumann lines in the present meteorite were

formed after it entered the atmosphere and followed its course downward to the earth.

This meteorite, which has retained some of the characteristics of a hexahedrite, will serve as an additional example, and perhaps

FIG. 54. Troilite inclusion bordered and traversed by schreibersite. Remnant grain boundaries distinctly visible. Etched 30 seconds with 5 per cent nitric acid in alcohol. ×32.

a typical one, to substantiate the generally accepted belief that ataxites are metamorphosed hexahedrites.

The only other nickel-poor ataxite from Arizona, recently described by Henderson and Perry (1949), is the Pima County meteorite. It was believed to have been found in the vicinity of Tucson, Pima County, Arizona. Both Navajo and Pima County meteorites agree remarkably well in their iron and nickel content but the two can be distinguished readily by the differences in certain of their structural constituents, particularly in the nature and distribution

of the schreibersite bodies. Comparisons show that Navajo, like Pima County, is a distinct meteorite and can not, at present, be assigned to any known type among the nickel-poor ataxites.

REFERENCES

COHEN, E.

1897. Ueber ein neues Meteoreisen von Locust Grove, Henry Co., Nord-Carolina [Georgia]. Sitzber. Berlin Akad., pp. 76–81.

1905. Meteoriten Kunde. Heft 3, pp. 44–47.

FOLEY, F. B. and CRAWSHAW, J. E.

1926. Effect of Air Gap in Explosion System on Production of Neumann Bands. Trans. Amer. Inst. Min. and Metall. Eng., **73**, pp. 948–963.

FOLEY, F. B. and HOWELL, S. P.

1923. Neumann Bands as Evidence of Action of Explosives upon Metal. Trans. Amer. Inst. Min. and Metall. Eng., **68**, pp. 891–915.

HENDERSON, E. P. and PERRY, S. H.

1949. The Pima County (Arizona) Meteorite. Proc. U. S. Nat. Mus., **99**, (3241), pp. 353–355.

MERRILL, G. P.

1922. New Meteorites. Amer. Jour. Sci., ser. 5, **3**, p. 154.

PERRY, S. H.

1944. The Metallography of Meteoric Iron. Bull. U. S. Nat. Mus., **184**. For illustrations of Locust Grove see pls. 10, fig. 2; 65; and 66, figs. 1 and 2; for Forsyth County see pl. 8, fig. 4.